

Further constraints on white dwarf galactic halos

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ABSTRACT

The suggestion that roughly half the mass of the galactic halo might be in the form of white dwarfs, together with the limits on the infrared background light and on the initial metallicity of the galactic disk, would set strong constraints on the initial mass function (IMF) of the halo. Particular IMFs have been proposed to cut off both the numbers of low-mass stars contributing to the infrared background and of high-mass stars which contribute to the growth of metallicity when they promptly explode as gravitational-collapse (Type II and Type Ib/c) supernovae. Here we examine the further contribution to metallicity from the Type Ia (thermonuclear) supernovae which would later be produced from the halo white dwarf population. We find that, for most of the evolutionary scenarios for the Type Ia supernova progenitor systems proposed so far, the constraints on the white dwarf mass fraction in the halo from the predicted production of iron would be extremely severe. When the predicted iron excess is not so large, then the exceedingly high Type Ia supernova rate predicted for the present time would also exclude a major contribution of white dwarfs to the halo mass. The white dwarf contribution, in all cases, should be below 5 – 10%. Besides, for the IMFs considered, the duration of the halo burst should be shorter than 1 Gyr in order to avoid too large a spread in the iron abundances of Population II halo dwarfs, and the predicted halo $[O/Fe]$ ratio would be at odds with observations.

Subject headings: galaxies: halos — galaxies: stellar content — stars: mass function — white dwarfs — supernovae: general

1. Introduction

Microlensing experiments (Bennet et al. 1996; Alcock et al. 1996) might indicate that roughly half of the mass in the halo of our Galaxy could be made of white dwarfs (WDs). The existence of such large numbers of WDs, the remnants of an earlier generation of halo stars, poses different problems. One of them is that as shown, for instance, by Adams & Laughlin (1996), the initial mass function (IMF) of the parent population of those WDs should have been very different from the IMF inferred for the galactic disk (see also Chabrier, Segretain, & Méra 1997; Fields, Mathews, & Schramm 1997). Otherwise, the low-mass tail of the IMF would give red dwarfs much in excess of their maximum allowed mass fraction in the halo (Graff & Freese 1996) while the high-mass end, by its metal production, would raise the initial metallicity Z of the galactic disk much above any reasonable level (unless the supernova products were ejected into the intergalactic medium). Far too luminous galactic halos (which should be seen at high redshifts) would also result from the large numbers of massive stars. From that double constraint, Adams & Laughlin (1996) deduce that the IMF of the WD progenitors should be confined within the mass range $1M_{\odot} \lesssim M \lesssim 8M_{\odot}$, and be sharply peaked about a characteristic mass $M_C \simeq 2.3M_{\odot}$. Even with such a IMF, due to the fact that only a fraction of the initial mass of the progenitor star stays trapped in the remnant WD, those authors (see also Isern et al. 1997) conclude that most likely the WD contribution to the halo mass should be 25% or less, 50% being an extreme upper limit. More recently, Gibson & Mould (1997) have examined the production of C, N, and O by the intermediate-mass star progenitors of the WDs. They find that the expected [C,N/O] ratios would be hard to reconcile with those measured in Population II halo dwarfs. Difficulties with models of WD-dominated halos are also pointed out by Venkatesan, Olinto, & Truran (1997). Earlier, Charlot & Silk (1995) had set upper limits to the WD fraction in galactic halos from the absence of the luminosity signature of the WD progenitors in deep galaxy surveys. It should be stressed that mass determinations

from gravitational microlensing are still uncertain (Mao & Paczyński 1996; Venkatesan, Olinto, & Truran 1997). Thus, possible incompatibilities with observational constraints must be taken into account before concluding that star formation in the halo should have been very different from that inferred for the disk.

In this *Letter* we look further into the problem of the metal enrichment of the galactic disk and halo by the putative parent population of the WDs. Massive stars ($M \gtrsim 8 - 10 M_{\odot}$) eject metals mostly at the end of their lives, when they explode as supernovae due to the gravitational collapse of their dense, fuel-exhausted cores. Phenomenologically, those are Type II (hydrogen-rich) and Type Ib/Ic (hydrogen-devoid) supernovae. Their progenitors are basically eliminated by adopting the IMF proposed by the aforementioned authors. However, the very population of halo WDs should give rise to another type of supernovae: thermonuclear supernovae (phenomenologically Type Ia, lacking hydrogen in their spectra). Type Ia supernovae (SNe Ia) are the explosions of some WDs (among those made of C+O) which ignite when they are compressed by mass accretion from a close binary companion. Those explosions yield an average of $\sim 0.6 M_{\odot}$ of iron, and it is estimated that they produce about 2/3 of the iron in the galactic disk (Bravo et al. 1993; Woosley & Weaver 1994), the other 1/3 coming from gravitational-collapse supernovae. Therefore, unless the binary frequency in the halo were very low and/or the distribution of initial binary parameters (mass ratios of the two components, binary periods) in the progenitor population of the halo WDs would strongly suppress the formation of close binary systems containing C+O WDs, one should expect a large contribution to the iron contents of the disk from a massive WD halo.

In the following we derive the time evolution of the iron mass produced by SNe Ia after an initial burst of star formation able to generate the presumptive WD halo population without violating neither the red dwarf nor the high-mass stars constraints. Whereas the

gravitational-collapse supernova rate can just be set equal to the massive star formation rate, the thermonuclear supernova (SNe Ia) rate depends on the evolutionary path assumed to produce the supernovae from a fraction of the close binary systems containing C+O WDs, together with the adopted distributions of initial binary parameters. We will thus discuss the dependence from those hypotheses of the iron production constraint on the mass fraction of WDs in the halo. We will see that in most cases the iron enrichment from SNe Ia would be incompatible with any substantial contribution of WDs to the halo dark matter. In the remaining cases, the exceedingly high SNe Ia rate predicted for the present time does also indicate that the mass fraction of the galactic halo in the form of WDs should be much smaller than that suggested from microlensing experiments. A further restriction to the hypothesis of particular IMFs giving rise to a large halo WD population comes from the comparison of the predicted spread in the iron abundances and the inferred $[O/Fe]$ ratios for Population II halo dwarfs with observational data.

2. Modeling, Results, and Discussion

We will assume that the parent population of the halo WDs forms in a burst lasting ~ 1 Gyr, with a IMF of the form:

$$\ln f(\ln M) = A - \frac{1}{2\langle\sigma\rangle^2} \left[\ln \left(\frac{M}{M_c} \right) \right]^2 \quad (1)$$

where A , M_c , and $\langle\sigma\rangle$ are constants (Adams & Laughlin 1996). A sets the total mass in the burst, and for M_c , the mass scale of the distribution, and $\langle\sigma\rangle$, its dimensionless width, the values $M_C = 2.3M_\odot$ and $\langle\sigma\rangle = 2.3$ are adopted. The IMFs proposed by Chabrier, Segretain, & Méra (1997) and by Fields, Mathews, & Schramm (1997) are similar and, to our present purpose, give equivalent results.

A fraction of the halo stars will be in binary systems whose initial parameters (primary mass, secondary/binary mass ratio, and separation between the two components) imply that they should eventually end up as a C+O WD plus a close companion. Mass transfer from the companion to the WD can then lead to explosive C ignition and a SNe Ia. Different scenarios have been proposed, depending on the nature of the companion (another C+O WD, a He star, a subgiant or red-giant star). We have considered all of them in order to calculate the SNe Ia rates and corresponding iron production following an outburst of star formation. Namely, the scenarios are: a) merging of a couple of C+O WDs (double-degenerate merging: DD); b) explosive ignition of He (followed by central ignition of C) at the surface of a C+O WD as a result of accretion from a He star companion (helium cataclysmic variable: HeCV); c) central explosive ignition of C as a result of mass growth by accretion from a red-(sub)giant companion (cataclysmic-like system: CLS); d) same as the previous case, but allowing higher mass-loss rates from the companion (“wind solution”: CLS(W)); e) explosive ignition of He (produced from burning of H) at the surface of a C+O WD accreting mass from the wind of a red-giant or supergiant companion (symbiotic system: SS). In scenarios a), c), and d) the exploding WD has reached the Chandrasekhar mass while in scenarios b) and e) the explosion takes place when a thick enough He layer has accumulated, the C+O WD mass being still below the Chandrasekhar mass. Most scenarios were already proposed in a seminal paper by Iben & Tutukov (1984) (see Iben 1997, for a recent review). The “wind solution” for the CLS scenario has been proposed by Hachisu, Kato, & Nomoto (1996). The characterization of the different SNe Ia scenarios considered here is as in Ruiz-Lapuente, Burkert, & Canal (1995) and Canal, Ruiz-Lapuente, & Burkert (1996) (see also Ruiz-Lapuente, Canal, & Burkert 1997). The results reported here correspond to the distributions of initial binary parameters adopted in those papers. We have also explored other suggested distributions, but the outcome was not significantly altered.

In Figure 1 we show the growth of the iron mass, M_{Fe} , following the halo star formation outburst, for scenarios a)–e). We will first assume that all the iron produced by the SNe Ia in the halo directly mixes with the gas in the disk and we will later discuss the possibilities of relaxing this hypothesis. The halo mass adopted is $M_{Halo} = 10^{12} M_{\odot}$ (its dynamical mass: see Peebles 1995). We take the disk mass $M_{Disk} = 0.1 \times M_{Halo}$. The relevant quantity, for our purpose, is the ratio M_{Fe}/M_{Disk} , that is the Z_{Fe} in the disk due to the halo contribution. As we see in Figure 1, in all scenarios M_{Fe} grows with time until reaching a maximum value at an epoch which corresponds to the explosion of the most slowly evolving SNe Ia progenitors formed in the halo outburst. The plateau value and the time at which it is reached depend on the scenario. As a conservative upper limit to the initial Z_{Fe} in the galactic disk we take half its solar value, $Z_{Fe\odot} = 1.7 \times 10^{-3}$ (Cameron 1982). Thus, $Z_{Fe}(0) \lesssim 8.5 \times 10^{-4}$. For our disk mass, that corresponds to $M_{Fe} = 8.5 \times 10^7 M_{\odot}$. Such a value is shown by the dashed horizontal line in the different panels of Figure 1.

We see that, unless most of the iron produced by SNe Ia from the halo WD population would not fall into the disk, in three of the scenarios considered (HeCV, CLS, and CLS(W)) the upper limit would already be reached at the end of the outburst (and even before that in the HeCV scenario), the iron mass rapidly growing up to much larger values afterwards. In the SS scenario, the limit would be reached at $t \simeq 0.5 \text{ Gyr}$ after the end of the burst. Later on, much larger iron masses are produced (it must be noted that the SNe Ia rates have been very conservatively calculated here: the SS efficiency in producing SNe Ia has been set to its lowest estimate). Only in the DD scenario the upper limit would not be reached until $t \simeq 1.5 \text{ Gyr}$ after the end of the burst, to slowly grow up to $\simeq 1.7$ times that, 10.5 Gyr later. The reason for the comparatively low SNe Ia rates in this scenario is that most of the progenitors of the DD mergers are within the initial mass range $6M_{\odot} \lesssim M \lesssim 8M_{\odot}$, which is not favored by a IMF of the form (1). Note that, for longer delays between halo and disk formation, the initial iron abundances in the disk would be higher.

In fact, the halo SNe Ia contribution to the iron enrichment of the disk would still be dominant at the time of birth of the Sun. Therefore, even neglecting the contribution from the SNe Ia and gravitational-collapse SN in the disk (and also the decrease in its gas contents due to previous star formation), the WD mass fraction in the halo should be $\lesssim 5 - 10\%$ (for the HeCV, CLS, and CLS(W) scenarios). From the iron argument alone, up to $\simeq 20\%$ would still be compatible with the SS prediction, and that for the DD scenario might even fit the microlensing estimate. However, as we will see next, consideration of the predicted SNe Ia rates for the present time do set more restrictive bounds.

SNe Ia rates. It is interesting to note that, in the DD and SS scenarios, SNe Ia should still be exploding in the halo at $t = 13 \text{ Gyr}$ after the start of the initial outburst. In the DD scenario, the rate would be $\nu_{SNeIa} \simeq 7 \times 10^{-3} \text{ yr}^{-1}$, whereas in the SS scenario it would be $\nu_{SNeIa} \simeq 2 \times 10^{-2} \text{ yr}^{-1}$. Even at $t = 18 \text{ Gyr}$ (a halo age suggested by Chabrier, Segretain, & Méra 1997), $\nu_{SNeIa} \simeq 4 \times 10^{-3} \text{ yr}^{-1}$ in the DD scenario, and $\nu_{SNeIa} \simeq 1 \times 10^{-2} \text{ yr}^{-1}$ in the SS one. All those values are far above observational upper limits. The only supernova observed in our Galaxy in the last 1,000 yr which clearly was a SNe Ia has been SN 1006 (van den Bergh & Tammann 1991), and its progenitor did not belong to the halo population. The argument that the historical supernova sample is not complete beyond a distance $\sim 3 \text{ kpc}$ applies to the thick disk population at most, but not to typical halo objects. Even at a distance $d \sim 20 \text{ kpc}$ (that is far out in the halo from our location within the Galaxy) the apparent blue magnitude of a SNe Ia at maximum would still be $m_B \simeq -2.5$ (about 1 mag brighter than Sirius). From this argument, a reasonable upper limit to the halo SNe Ia rate should be at least one order of magnitude below that predicted by the DD scenario, which would again put the contribution of the WD population to the halo mass below $5 - 10\%$. Consideration of the rate of merging of WD pairs in the halo population strengthens this conclusion, since it should occur at rates $\nu_{merg} \simeq 0.4 \text{ yr}^{-1}$ (13 Gyr) or $\nu_{merg} \simeq 0.3 \text{ yr}^{-1}$ (18 Gyr). Most of them would not produce any SNe Ia but a hot

WD, which would remain very luminous for $\sim 10^8$ yr. Their total population should thus be $\sim 3 - 4 \times 10^7$ nowadays and it would hardly have escaped detection.

The halo gas component. In the preceding we have assumed that most of the material ejected by the SNe Ia mixes with the gas in the galactic disk. If the halo were left completely gas-free after the initial burst of star formation, one should expect that roughly half the SNe Ia ejecta would escape the Galaxy whereas the other half would hit the disk and mix with the gas there (typical velocities of the ejecta are larger than the escape velocity from the galactic halo and there would not be halo gas to slow them down). However, as pointed out by Adams & Laughlin (1996), Isern et al. (1997), and Gibson & Mould (1997), the intermediate-mass star progenitors of the WDs should return typically $\simeq 50 - 75\%$ of their mass to the interstellar medium through stellar winds and planetary nebula ejection. The time scale of such mass ejection is shorter than that of growth of the iron mass from SNe Ia (especially in the case of the DD and SS scenarios). Therefore, much of this gas should mix with the iron-rich SNe Ia ejecta. In that case, the iron would be much more diluted than if it were only mixed with the gas in the disk. There is, however, the problem of where this halo gas might be hidden (it cannot fall into the disk, since otherwise the latter would be much more massive than it actually is). One possibility is that it would be concentrated into cold molecular clouds (De Paolis et al. 1997). In that case, since formation of most clouds would precede ejection by the SNe Ia of a major fraction of the iron mass and the filling factor of the clouds should be small, the case would resemble that of a gas-free halo. Another possibility is that heating of the halo gas by the SNe Ia explosions might be enough to generate a strong galactic wind and eject most of the gas. A first estimate of the energy budget shows that this possibility is only marginal. Summarizing, in any case the problem of the halo gas component, rather than rising the upper limit to the WD mass in the galactic halo, strengthens the conclusion that it should be smaller than the total mass in the galactic disk and make $\lesssim 5 - 10\%$ of the halo mass only.

Halo dwarf metallicities and $[O/Fe]$ ratios. As it can already be seen in Figure 1, even within a burst of star formation lasting ~ 1 *Gyr*, there should be an appreciable variation in the iron contents of the gas from the beginning to the end of the burst, due to the SNe Ia exploding during this time interval. That should translate into a range of abundances $[Fe/H]$ within the halo Population II dwarfs. The predicted range will depend on the duration of the burst, on the time variation of the star formation rate within the burst, and on the SNe Ia scenario. In Figure 2 we compare the growth with time of the iron abundance for the stars formed in the halo burst (lasting 1 *Gyr*), among the scenarios a)–e) considered above, and assuming a constant star formation rate. We see that, for any scenario, a significant spread in the iron abundances among halo dwarfs should be expected. A fraction of dwarfs would show near–solar iron abundances (and even higher, for the HeCV scenario). The measured spread is $-3.5 \lesssim [Fe/H] \lesssim -1$ (Schuster & Nissen 1989). Agreement could be obtained in all cases by shortening the duration of the burst, but that would be in conflict with evidence of a scatter $\sim 2 - 3$ *Gyr* in the ages of those stars (*ibid.*). A more difficult problem is that SNe Ia explosions alone would always give $[O/Fe] \simeq -1.4$ (-1 being an extreme upper limit) while the observed $[O/Fe]$ in halo dwarfs is $\gtrsim +0.5$ (and thus bears the signature of massive star nucleosynthesis) (Barbuy 1988; Abia & Rebolo 1989; Spite & Spite 1991; Spiesman & Wallerstein 1991). Therefore, not only the duration of the halo burst should be extremely short to avoid contamination by the SNe Ia products, but in addition some even earlier generation of massive stars should have produced the $[O/Fe]$ actually measured. That appears unlikely.

3. Conclusions

If a large fraction of the galactic halo mass were made of WDs, one would expect a large iron production from the SNe Ia arising from a fraction of the WDs belonging to

close binary systems. Since both the total iron yield and its time evolution depend on the evolution assumed for the SNe Ia progenitors, we have considered all the main SNe Ia scenarios proposed so far: double degenerate merging, He-star cataclysmic systems, two different versions of the cataclysmic-like scenario, and symbiotic systems. The results for each evolutionary path are fairly insensitive to the choices of the initial binary parameters (distribution of mass ratios of the secondary to the primary, distribution of initial separations). The IMF is chosen to minimize the numbers of both red dwarfs and high-mass stars.

Assuming that most of the iron produced by the SNe Ia in the halo mixes with the gas in the disk, the constraint that Z_{Fe} at the time of birth of the Sun should not exceed $Z_{Fe\odot}$ sets upper limits $\simeq 5 - 10\%$ to the WD mass fraction in the halo for the HeCV, CLS, and CLS(W) scenarios. Comparison of the predicted SNe Ia rates for the present time with observational upper limits set similar bounds for the SS and DD scenarios. Besides, a halo burst with IMFs such as those tested here would produce too large a spread in the iron abundances of Population II halo dwarfs unless it lasted less than 1 Gyr, which would conflict with evidence of a wider range of ages among those stars. Worse still, the O/Fe ratio should be far below solar while the measured ratio is much larger than solar, as one would expect from massive star nucleosynthesis, and that hardly fits with the proposed halo IMFs.

Consideration of the role that the SNe Ia originated in the halo WD population would play in the evolution of the Galaxy, thus points in the same direction as that of the fate of the gas ejected by the WD progenitors (Adams & Laughlin 1997; Isern et al. 1997) and that of the [C,N/O] ratios which would result (Gibson & Mould 1997): the WD mass fraction in the galactic halo should be much lower than that suggested from microlensing experiments. Our derived upper bounds are even lower than those set from number counts

in deep galaxy surveys.

As a more general conclusion, we can say that the proposal of *ad hoc* IMFs to explain a presumptive huge halo WD population poses problems which could only be solved by assuming that the whole process of star formation (single as well as binary stars) in the galactic halo has been completely different from all we know from local observations. Since the existence of a massive WD halo is by no means firmly established, it is premature to make so many *ad hoc* assumptions.

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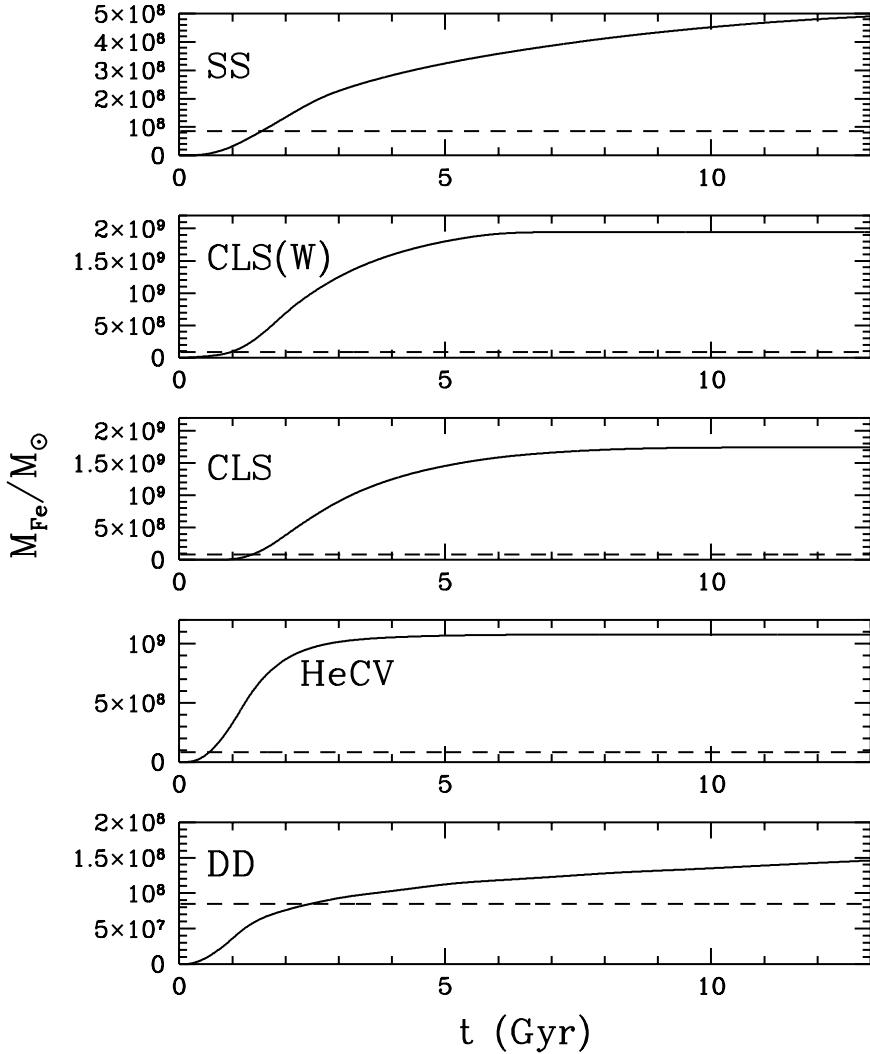


Fig. 1.— Growth of the iron mass produced by SNe Ia following the start of a burst of star formation in the halo, lasting for 1 *Gyr* and involving $10^{12} M_{\odot}$, for the five different SNe Ia scenarios considered (see text). The horizontal dashed line corresponds to $M_{Fe} = 8.5 \times 10^7 M_{\odot}$, the amount which mixed with $M_{Disk} = 10^{11} M_{\odot}$ of unenriched gas would give $Z_{Fe} = \frac{1}{2} Z_{Fe\odot}$. Note the different scales from one panel to another.

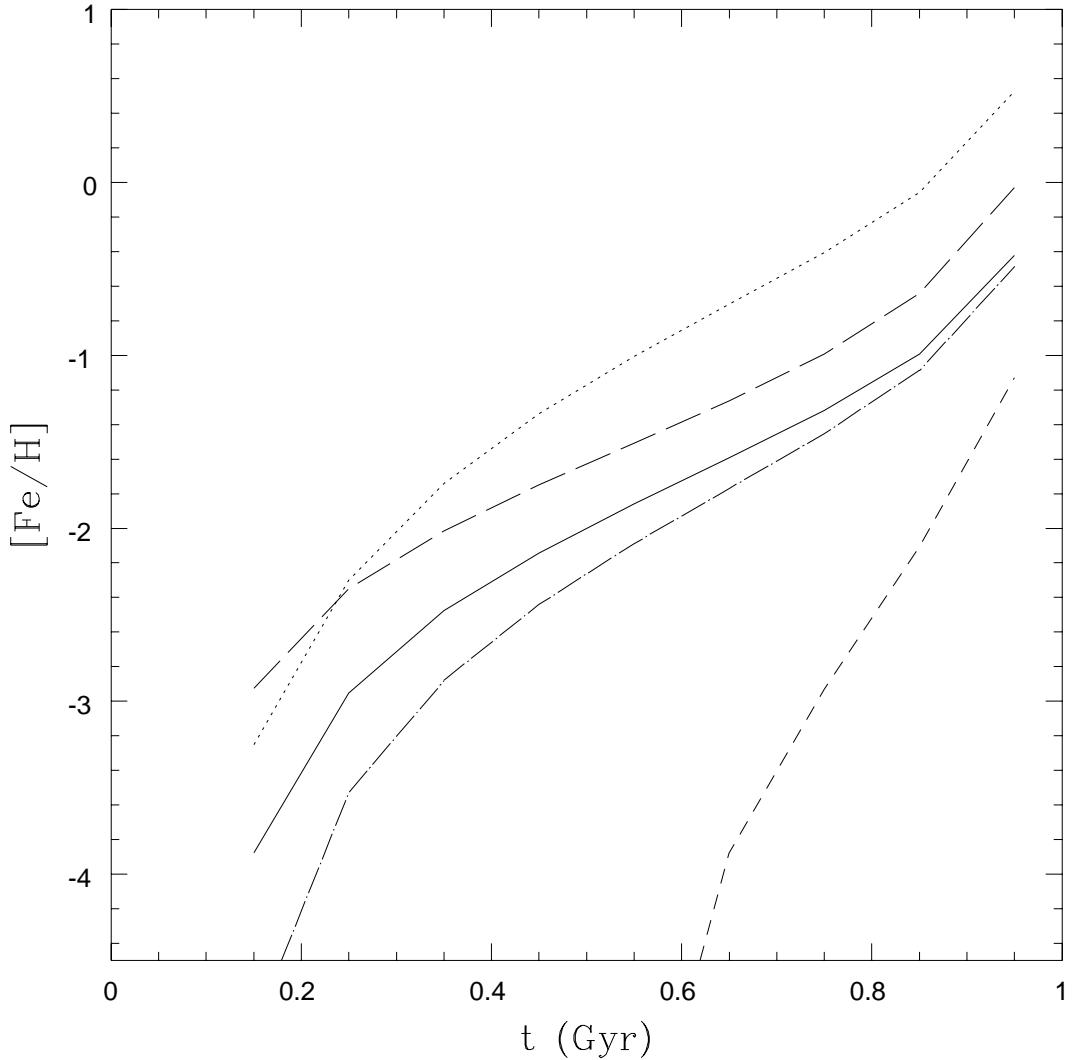


Fig. 2.— Growth with time, during the burst, of the iron abundance in Population II halo dwarfs, for scenarios a)–e), assuming a constant star formation rate. Continuous line: DD; dotted line: HeCV; short-dashed line: CLS; long-dashed line: CLS(W); dot-dashed line: SS (see text and Figure 1).